ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20240502092606

Original scientific paper
Received: 2024-05-02, Accepted: 2024-05-08

# Injection Moulded Part Analysis by Alignment of Simulated and Referent Part Geometry

Damir Godec*, Filip Panđa, Mislav Tujmer

**Abstract:** Warpage of the injection moulded parts is one of the most common defects after demoulding, which is intensively present in thin-walled moulded parts or parts with non-uniform wall thickness. The level of the warpage can be reduced by optimizing the mould tempering system in the phase of mould design, by optimizing the injection moulding parameters and recently by optimizing the shape of the mould cavity elements geometry – so-called inverse contouring. Computer simulation of injection moulding process can show the level of moulded part warpage after ejection from the mould, but it will not allow detailed measuring of critical moulded part measures deviations. Detailed analysis and prediction of the critical moulded part dimensions can be performed by aligning of the deformed moulded part design obtained with computer simulation, with moulded part reference CAD geometry. This paper shows the main steps and an example of the geometry aligning process for a specific thermoplastic part.

**Keywords:** injection moulding; moulded part geometry alignment; numerical simulation

## 1 INTRODUCTION

The modern development of injection moulded polymer parts is directed towards sustainable production, where one of the key measures is the reducing of the moulded part wall thickness. The reason lies not only in reduction of thermoplastic material consumption, but also in significant reduction of the injection moulding cycle time. However, such thin-walled moulded parts are very challenging from the processing point of view because they require high processing parameters, and in addition, they are more prone to deformation after removal from the mould cavity during cooling, most often in the form of warpage. [1] The level of warpage can be reduced by optimizing the mould tempering system in the phase of its design [2], by optimizing the injection moulding parameters [3] and recently by optimizing the shape of the mould cavity elements geometry – so-called inverse contouring [4]. Computer simulation is a powerful tool for predicting behaviour of observed products/systems [5], and in case of injection moulding it is a tool for predicting the critical occurrences during the injection moulding cycle, as well as for prediction of the level of moulded part warpage after ejection from the mould [6].

On the other hand, injection moulding simulation will not allow detailed measuring of critical moulded part measures deviations. Detailed analysis and prediction of the critical moulded part dimensions can be performed by aligning the deformed moulded part design obtained with computer simulation, with moulded part reference CAD geometry [6]. This paper shows the main steps and an example of the process of aligning deformed moulded part geometry of specific thermoplastic part with reference geometry.

## 2 INJECTION MOULDED PART WARPAGE

Warpage of injection moulded parts is one of the most common visible defects caused by a few factors, the most frequent of which is non-uniform shrinkage of the moulded part during the cooling phase in the mould. If the shrinkage of the moulded part is uniform in all directions, the moulded part will not warp, and it will not change its shape. There will only be a uniform decrease of its dimensions, which can be compensated by simply increasing the dimensions of the referent moulded part CAD model for mould design [6].

**Figure 1** Example of moulded part warpage [1]

There are several significant influencing factors on non-uniform moulded part shrinkage, like molecular and/or reinforcement orientation (in flow direction of polymer melt in the mould cavity) during mould filling phase, cooling process of polymer melt in the mould cavity, non-uniform mould temperature field (Fig. 2) and non-uniform moulded part wall thickness. [7]

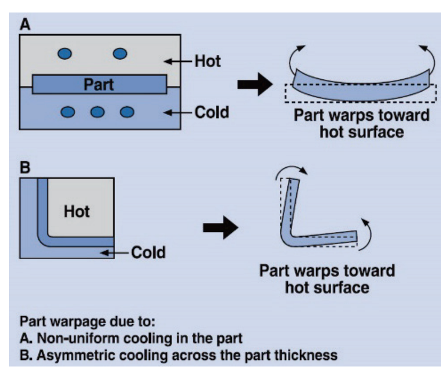


**Figure 2** Moulded part warpage due to uneven mould temperature field [7]

Type of the processed polymer material, parameters of injection moulding process, geometry of the moulded part, mould design, mould tempering system as well as type, number, dimensions and position of the gates, are also significant influencing factors on moulded part shrinkage and warpage. Fig. 3 shows the influence of injection moulding parameters on moulded part shrinkage. [8]

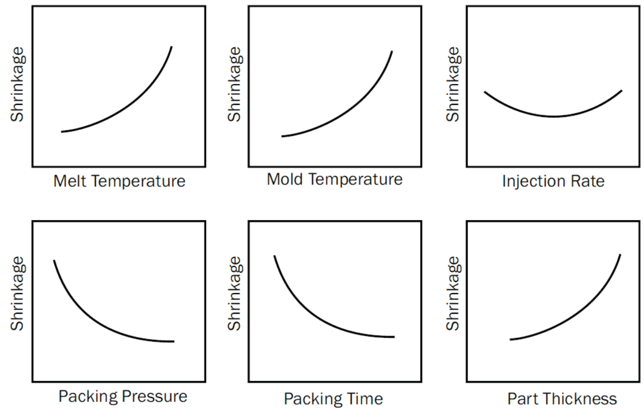


**Figure 3** Influence of injection moulding parameters on moulded part shrinkage [8]

In the past, determination of shrinkage and warpage of polymer moulded part was one of the most complicated tasks in mould design process, but today, thanks to the detailed and precise numerical computer simulations, it is possible to estimate final shape and dimensions of the moulded part, even before production of the mould.

Software for simulation of injection moulding, mostly based on *Finite Element Method* (FEM) have been developed to simulate the processing of the polymer material from a melt phase at the start of injection phase to a solidified product at the time of ejection. The aim of these applications is to predict and understand the causes of shrinkage and warpage, which might occur during injection moulding.

Although numerical simulation of the injection moulding process can give an overall insight into moulded part warpage, when more precise measurements of dimensional deviation from referent part are necessary, raw simulation results are not suitable for estimating detailed deviations of critical dimensions and/or shape of the moulded part necessary for redesigning moulded part and mould cavity elements.

## 3 MINIMIZING INJECTION MOULDED PART WARPAGE

This paper shows optimisation of moulded part design for minimizing moulded part warpage after ejection from the mould cavity. Several numerical simulations of injection moulding process were performed, and warpage of injection moulded part depending on moulded part design was observed as a result. Software package *Autodesk Moldflow Insight* was used for that purpose.

Referent moulded part was a component of automotive connector – a handle for reducing the assembly force necessary for connector plug-in (Fig. 4). Polymer material for production of the handle is thermoplastic polybutylene terephthalate (PBT) reinforced with 20 % of glass fibres.

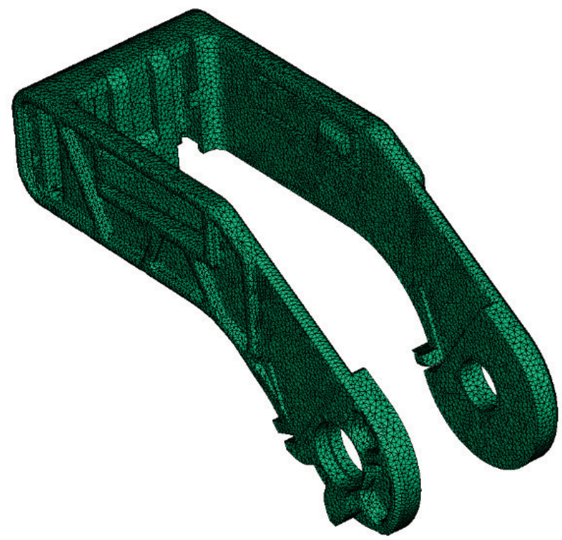

**Figure 4** 3D mesh model of a handle [6]

### 3.1 Determination of the Gate Position

The first step in optimization process of handle is determination of optimal gate position. Figure 5 shows optimal area (blue colour) determined by software analysis *Gate Location*.

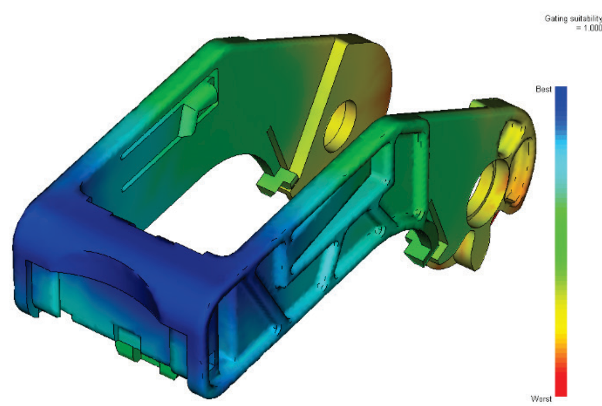


**Figure 5** Results of *Gate Location* analysis [6]

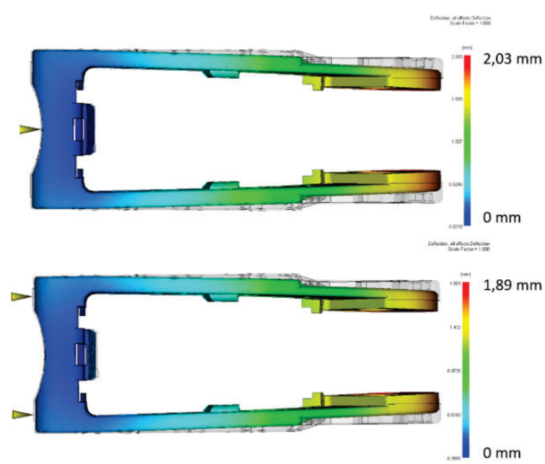


**Figure 6** Warpage differences – single and two gates cavity [6]

Analysis of the influence of application more gates was performed within the next optimization step. Analysis sequence *Fill* + *Pack* + *Warp*, which encompasses analysis of mould cavity filling, phase of acting packing pressure and warpage analysis based on previous two analysis, was used for this purpose. Based on results shown on Fig. 6, application of two gates per cavity resulted with reduction of maximum warpage for 0,15 mm (for 7,3 %), and therefore a simulation model with two gates was used for further analyses.

### 3.2 Initial Injection Moulding Analysis

Within simulation model, moulded part is set into a steel mould with dimensions 75 × 135 × 100 mm. The mould has integrated 6 mm diameter cooling channels, and for all inlets of cooling media (water) the temperature is set to 85 °C. Initial analysis of injection moulding was performed with this model for detailed determination of warpage value of observed moulded part. Analysis sequence *Cool* + *Fill* + *Pack* + *Warp* was used because it includes influence of mould cooling system to the moulded part warpage. Figures 7 and 8 are showing average mould temperature fields in vertical and horizontal mould plane cross-sections.

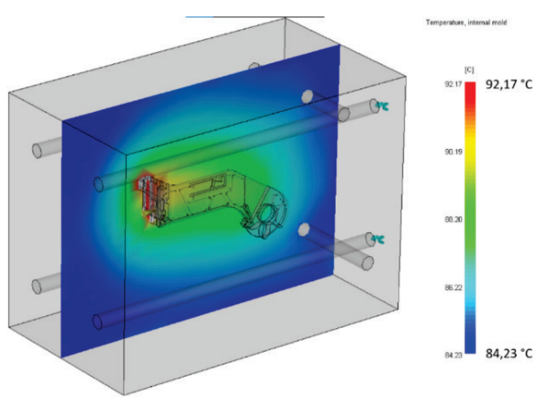


**Figure 7** Cool analysis – vertical mould plane cross-section [6]

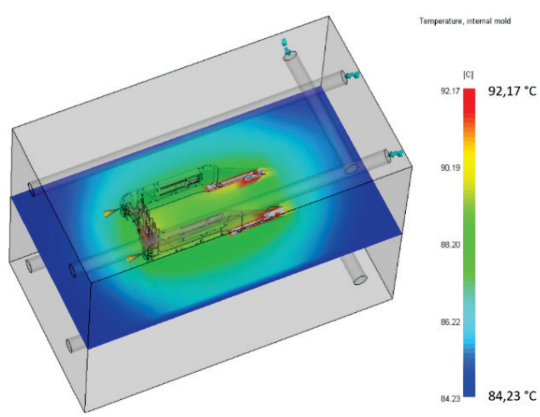


**Figure 8** Cool analysis – horizontal mould plane cross-section [6]

Analyses of the filling phase and the phase of acting packing pressure (*Fill* + *Pack*) are performed after *Cool* analysis. Tab. 1 shows some of the results obtained with this analysis which provide important information for running injection moulding process as well as for evaluation of suitability of processing on specific injection moulding machine.

**Table 1** Simulated injection moulding parameters [6]

| | Value | Unit |
|---|---|---|
| Filling time | 0,63 | s |
| Max. injection pressure | 27,6 | MPa |
| Mould clamping force | 18,93 | kN |
| Moulded part cooling time | 2,95 | s |

Last analysis in this sequence is warpage analysis (*Warp*). This analysis provides estimation of moulded part shrinkage and warpage. The results are shown as displacements of the nodes within finite element mesh, compared with initial position, for amounts in $x$, $y$ and $z$ directions (Cartesian coordinate system). This enables to observe results depending on each axis separately, or as a total displacement, where displacement of each mesh node is calculated according to Pythagorean Theorem.

Fig. 9 shows total displacements of nodes within mesh of the moulded part – top and isometric view [6].

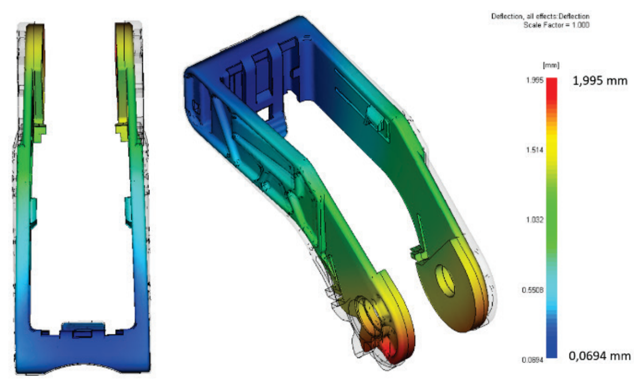


**Figure 9** Warpage analysis [6]

Here, it is important to emphasise that presented displacements cannot be used for more precise measuring of deviations from referent geometries until warped moulded part is aligned with referent geometry.

### 3.3 Alignment of Warped Moulded Part with Referent Geometry

Software package Autodesk Moldflow enables exporting of deformed moulded part geometry in form of STL file. Resulting STL file is a mesh of connected triangles, which represents surface geometry of the moulded part. Deformed geometry in STL file consists of the same number of elements like initially generated *Dual Domain* mesh, which determine moulded part surface geometry. The location of nodes in this mesh is different compared to their initial locations due to shrinkage and warpage of the moulded part. For alignment of warped moulded part geometry with referent, *GOM Inspect* software was used. *GOM Inspect* is a software for non-contact measuring in product development phases, production and quality control. Data for the analysis are mainly provided with 3D scanning or computer tomography (CT scanner), but in this paper, exported geometry from software *Autodesk Moldflow* was used instead of data of scanned part.

GOM Inspect distinguishes two types of geometry – wanted (ideal) geometry in form of CAD body named as Nominal, and deformed mesh named as Actual geometry.

For analysis presented in this paper, in the first step automatic initial alignment (*Prealignment*) was performed, and in second step manual alignment according to generated geometrical element (*Alignment By Geometric Elements*) [6].

Fig. 10 shows initial alignment of moulded part deformed geometry with referent geometry. White colour represents referent CAD geometry, and green colour deformed geometry in STL format exported from *Autodesk Moldflow* analysis. [6]

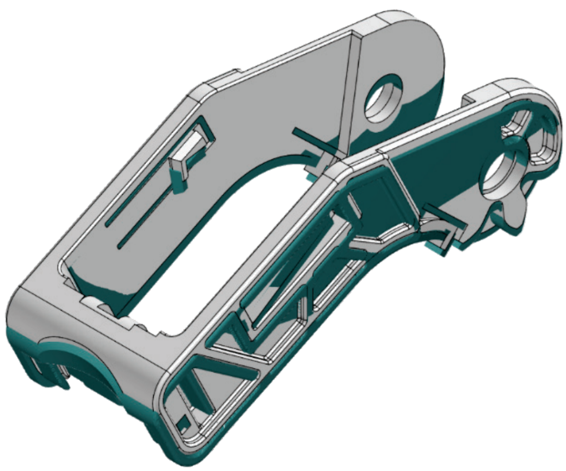

**Figure 10** Initial alignment deformed and referent geometry (*Prealignment*) [6]

Disadvantages of such alignment are the most visible at rear surface of moulded part. Although the software with automatic search function found nodes that match each other, geometries generally are not aligned well, therefore such aligned geometry cannot be considered for further analysis. Therefore, it is necessary to perform alignment by manually generated geometrical elements, such are nodes, planes, lines, cylinders, etc.

In all analyses in this paper, referent and deformed geometries are aligned by three planes – two symmetric planes generated between side walls, and one on the rear side of the moulded part. One of the alignments is shown on Fig. 11 [6].

The planes should be generated separately on referent and deformed geometry. Planes on referent geometry have no attached measuring principle, since it is not necessary for it, while at deformed geometry surface have assigned *Fitting Element* measuring principle with which selected nodes on the plane are projected at nominal geometry for assuring the most accurate measuring results.

Additional problem while generating the planes on deformed geometry is in difficulties in recognizing of deformed planes because relatively small number of nodes which are present in STL mesh, despite the element size of approximately 0,4 mm. Measuring software have code written for the meshes with large number of polygons generated from point cloud obtained with scanning of real objects, therefore in this research the mesh is refined using the *Refine Mesh* function within *GOM Inspect* software. Two refining iterations were used, which resulted in increasing the number of polygons of a specific surface approximately 6 times. Thus, smaller triangles were generated within existing ones, therefore the software has more nodes for generating planes on deformed geometry [6].

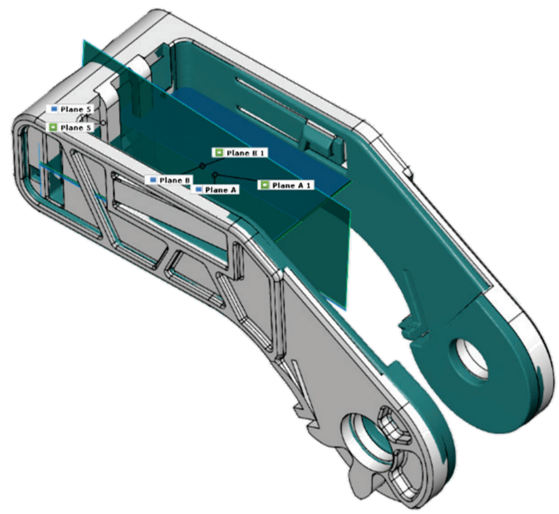


**Figure 11** Alignment of deformed and referent geometries by defined geometric elements (*Alignment By Geometric Elements*) – isometric view [6]

From Fig. 11 it is obvious that, after alignment by geometric elements, both geometries are much better aligned at rear side of the moulded part, which is more dimensionally stable, while side walls are extremely deformed inwards [6].

Fig. 12 shows alignment of warped and referent geometry by geometric elements from top view.

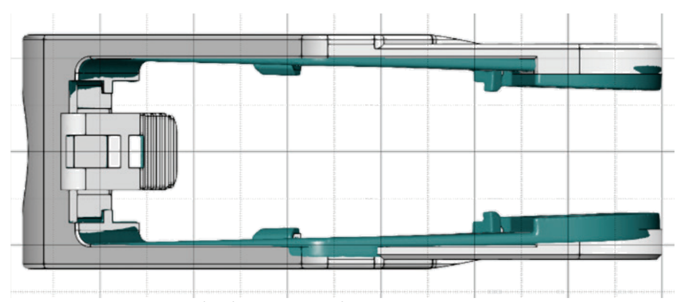

**Figure 12** Alignment of deformed and referent geometry by geometric elements (Alignment By Geometric Elements) – top view [6]

### 3.4 Results of Alignment – Surface Comparison

When all parts are correctly aligned, using the *Surface Comparison on CAD* function it is possible visually present how much deformed (warped) geometry deviates from the referent. Software *GOM Inspect* calculates deviation as an orthogonal distance each node in the mesh from related position in referent CAD geometry and results are shown in different colours at copy of referent CAD geometry.

Figure 13 shows the deviations of nodes on deformed geometry from referent. Green colour at image marks regions where characteristics of deformed geometry matches the best with characteristics of referent CAD geometry. Red and blue colours present zones of maximal deviation of deformed geometry.

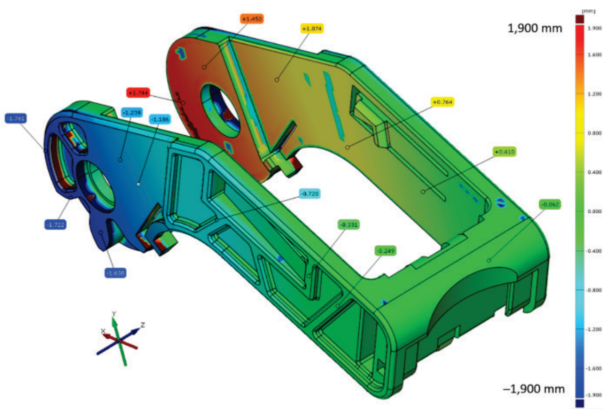


**Figure 13** Deviations of nodes at deformed geometry compared with referent geometry (Surface Comparison on CAD - *GOM Inspect*) [6]

From the results it is obvious that maximal deviation of the moulded part is approximately 1,8 mm on side moulded part walls. From Figs. 12 and 13 it can be concluded that side part walls are almost linearly warped inwards, therefore it is possible to calculate the angle of inclination $\alpha$ with determination of length of thinner side part approximately 57,5 mm.

$$\alpha = \sin^{-1}\left(\frac{1,8}{57,5}\right) = 1,79°. \quad (1)$$

### 3.5 Referent Moulded Part Inverse Contouring

For reduction of moulded part warpage there are few strategies. The simplest approach is optimisation of injection moulding parameters for minimizing moulded part warpage, but this approach often will not result with satisfying warpage reduction or results with to long injection moulding cycles. The second strategy is oriented to optimal mould tempering, however, design mould characteristics often will not allow application of optimal shapes and configurations of mould tempering channels. Within this strategy, application of additive manufacturing allow production of co-called conformal cooling system, but on the other hand, this approach results with increased mould production costs and it is reasonable only in case of large batch or mass production.

Therefore, in this case the third strategy is imposed – correction of the moulded part (and appropriate mould cavity elements) geometry, using which warped geometry after injection moulding will converge to the referent moulded part geometry – inverse contouring. The main goal of inverse contouring is to minimize moulded part warpage by deliberately extracting walls in opposite direction of the warpage, which will result with aimed dimensions and shape of final moulded part. In that case, mould cavity elements are designed in opposite direction of moulded part warpage tendency. This strategy enables easier achieving moulded part dimensional specifications, avoiding mould redesign, expensive corrections and fastest moulded part validation, which all in general result with shorter time from idea to final product ready for the market.

In case of observed handle, the most important task is to achieve flatness of sidewalls. Without inverse contouring, those walls will be notably warped inwards. As the previous analysis shows that side walls will be deformed inwards under the angle of approximately 1,79°, in moulded part process, side walls are extracted outwards under the angle of 1,8° (Fig. 14).

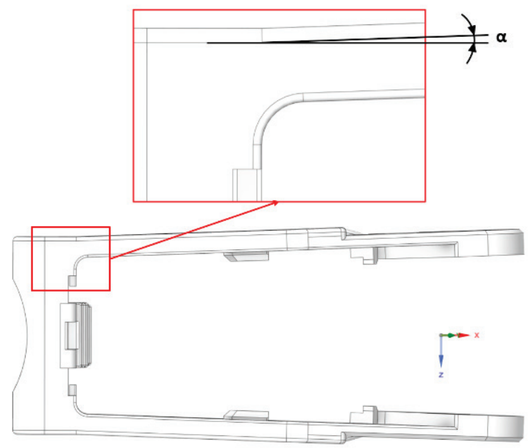


**Figure 14** Moulded part geometry after inverse contouring [6]

The process of computer analysis of injection moulding is repeated with such, purposely deformed moulded part geometry. Warpage results obtained in software *Autodesk Moldflow* are again imported in GOM Inspect software in form of STL file, and process of geometry alignment is repeated. Fig. 15 shows results of alignment of moulded part inverse contoured geometry and referent part geometry [6].

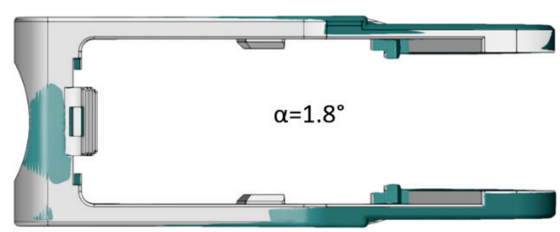


**Figure 15** Alignment of warped inverse contoured moulded part geometry with referent geometry [6]

After alignment with function *Surface Comparison on CAD*, *GOM Inspect* software calculates deviations of inversed contour geometry from referent geometry. Results of comparison of deviations of deformed geometries without inverse contouring and with inverse angle 1,8° are shown in Fig. 16.

By application of extraction angle on side walls of handle, maximal deviation of side walls is reduced from approximately 1,8 – 1,9 mm to approximately 0,2 – 0,3 mm, (warpage reduction for more than 80 %).

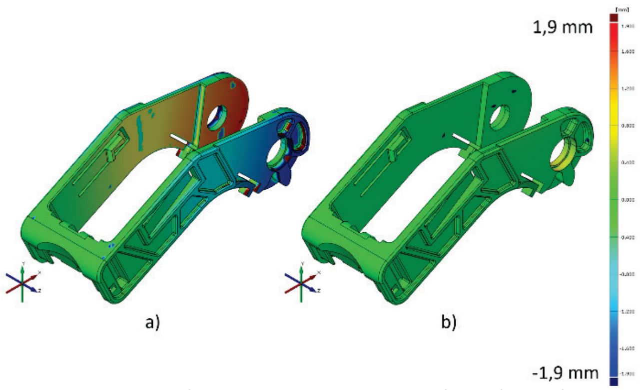


**Figure 16** Deviation of warped moulded part geometry from referent: a) without inverse contouring, b) with inverse contouring angle $\alpha$ =1,8° [6]

## 4 CONCLUSIONS

This paper presents process of injection moulded part geometry optimisation with alignment of deformed geometry obtained with computer simulation of injection moulding process and referent moulded part geometry. Inverse contouring is also presented as one of the tools for optimisation of deformed geometry for achieving minimal warpage values. This moulded part geometry optimisation principle can be useful for the companies whose main business is polymer moulded part development and processing with injection moulding.

Presented example shows decrease of warpage at important moulded part zones by more than 80 % with relatively simple changes in moulded part and mould design. Application of this optimisation principle can result with production of more dimensionally accurate moulded parts and easier validation of production during phase of testing and quality control.

In the mold and die making stage, numerical simulation can be used as a tool for accurate estimation of the zone of moulded part warpage and real deviations of the geometry from referent moulded part geometry can be obtained by analysing warped moulded part within specialised software for metrology. The complete presented process can be performed even before the mould and moulded part are produced.

## 5 REFERENCES

[1] Jyo, C. (2023, August 7). The Causes and Solutions of Warping in Injection Molding. https://prototool.com/warping-in-injeciton-molding/

[2] Mohd Hanid, M. H., Abd Rahim, S. Z., Gondro, J., Sharif, S., Al Bakri Abdullah, M. M., Zain, A. M., El-hadj Abdellah, A., Mat Saad, M. N., Wysłocki, J. J. & Nabiałek, M. (2021). Warpage Optimisation on the Moulded Part with Straight Drilled and Conformal Cooling Channels Using Response Surface Methodology (RSM), Glowworm Swarm Optimisation (GSO) and Genetic Algorithm (GA) Optimisation Approaches. *Materials, 14*(6), 1326-1326. https://doi.org/10.3390/ma14061326

[3] Hiyane-Nashiro, G., Hernández-Hernández, M., Rojas-García, J., Rodriguez-Resendiz, J. & Álvarez-Alvarado, J. M. (2022). Optimization of the Reduction of Shrinkage and Warpage for Plastic Parts in the Injection Molding Process by Extended Adaptive Weighted Summation Method. *Polymers, 14*(23), 5133. https://doi.org/10.3390/polym14235133

[4] Hopmann, C., Gerads, J. & T. Hohlweck. (2021). Investigation of an inverse thermal injection mould design methodology in dependence of the part geometry. *International Journal of Material Forming, 14*(2), 309-321. https://doi.org/10.1007/s12289-020-01604-6

[5] Daneshjo, N., Mares, A., Malega, P. & Francova, Z. (2022). CAD Model of Rear-View Mirror and Simulation of Its Aerodynamics and Noise. *International Journal of Simulation Modelling, 21*(2), 226-236. https://doi.org/10.2507/ijsimm21-2-598

[6] Pandža, F. (2023). Optimisation of moulding design for minimisation of warpage. *M.Sc. Thesis*, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb.

[7] Design Guide Performance and Value with Engineering Plastics. (n.d.). Retrieved March 19, 2024, from http://www.hankyan.com/design_guide_with_engineering_plastics_by_0DSM.pdf

[8] Fisher, J. M. (2013). *Handbook of Molded Part Shrinkage and Warpage*. 2nd Edition. William Andrew Publishing, ISBN 978-1-4557-2597-7.

**Authors' contacts:**

**Damir Godec**, Full Professor PhD
(Corresponding author)
University of Zagreb,
Faculty of Mechanical Engineering and Naval Architecture,
Ivana Lučića 5, 10000 Zagreb, Croatia
damir.godec@fsb.unizg.hr

**Filip Panđa**, mag. ing. mech.
YAZAKI-EUROPE Ltd.
Slavonska avenija 26/6, 10000 Zagreb, Croatia
filip.pandja@yazaki-europe.com, filippandja@gmail.com

**Mislav Tujmer**, mag. ing. mech.
University of Zagreb,
Faculty of Mechanical Engineering and Naval Architecture,
Ivana Lučića 5, 10000 Zagreb, Croatia
mislav.tujmer@fsb.unizg.hr